Neutrinos in Cosmology

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Snowmass on the Mississippi, 6/30/13

introduction

- Cosmology is our best hope to measure neutrino mass in the coming decade
- I will review neutrino physics in cosmology and introduce two parameters to which cosmology is mainly sensitive:
  - Sum of neutrino mass eigenstates $\sum m_\nu$
  - Effective number of neutrino species $N_{\rm eff}$ (parameterizing any extra relativstic d.o.f.)
- Briefly overview relevant probes and their dominant systematics

particle physicist's view

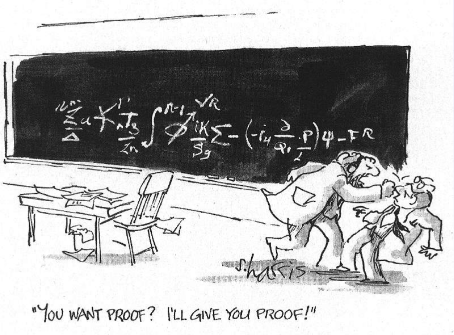
Common misconceptions:

- It all depends on the "assumed model"
- More than one numerical result means that we "don't understand systematics"
- Systematics will never get better

From André de Gouvêa's talk at Brookhaven Forum 2011:

Bounds can be evaded with non-standard cosmology. Will we learn about neutrinos from cosmology or about cosmology from neutrinos?

Recent ν Results



neutrino physics

- We see indisputable evidence for neutrino oscillations:
  - Atmospheric: $\nu_\mu \to \nu_\tau$,$\bar{\nu}_\mu \to \bar{\nu}_\tau$
  - Solar: $\nu_e \to \nu_\mu, \nu_\tau$
  - Accelerator: $\nu_\mu \to \nu_e, \nu_\tau$
  - Reactor: $\bar{\nu}_e \to \bar{\nu}_\mu, \bar{\nu}_\tau$
- These observations are explained by introducing a neutrino mass term:

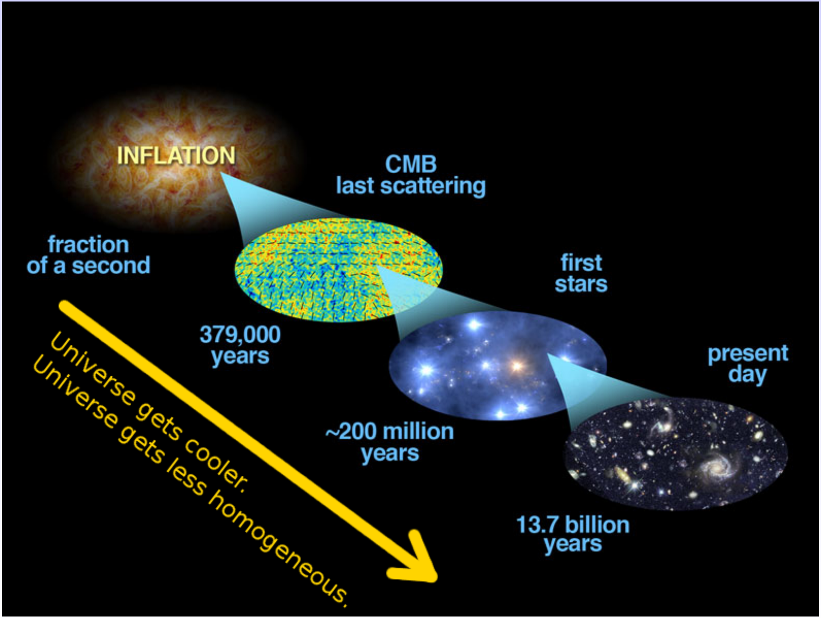
$$\mathcal{L}_m = -\bar{\nu}_R \mathrm{U}^* \mathrm{M} \mathrm{U} \nu_L + \mathrm{h.c.}$$

  - *M* A diagonal 3×3 matrix telling how heavy each eigenstate
  - *U*: A unitary 3×3 matrix telling how much mass eigenstate in each flavour eigenstate

free parameters

- **Particle Physics (does not enter cosmology):**
  Unitary matrix U has 9 d.o.f. After removing nonphysical phases, we parametrise it in terms of
  - 3 angles θ_{ij},
  - CP-violating phase δ
  - 2 Majorana phases $\alpha_{1,2}$ (if Majorana)
- **Thermodynamics/Gravity (enters cosmology):**
  - 3 masses m_i that determine M
- Probes of ν physics
  - Neutrino oscillation experiments: θ_{ij}, $m_i^2 - m_j^2$
  - Tritium β-decay: effective m_{ν_e}
  - Netrinoless β-decay: is Majorana?, m
  - **Cosmology:** $\sum m_i$, (m_i)

universe's timeline



neutrinos in cosmology

- Universe homogeneous when neutrino background is formed
- Assuming **massless**, neutrinos are like photons, except:
  - **decouple before** e^--e^+ annihilation:
    - Temperature ratio can be calculated assuming conservation of entropy:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.95\mathrm{K}$$

      (note $T_\gamma = T_{\mathrm{CMB}} = 2.72548 \pm 0.00057$. $n \sim 56/\mathrm{cm}^3$, but very cold)
  - **fermions** rather than bosons:
    - Contribute 7/8 of photon energy density at the same temperature:
  - **3 generations** of ν, $\bar{\nu}$
  - Hence:

$$\rho_\nu c^2 = 3 \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma c^2$$

- **In terms of energy density, neutrinos as important as radiation!**

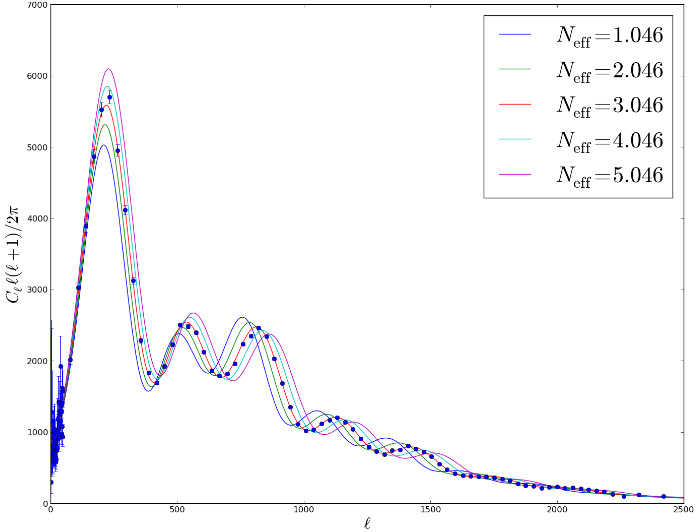
N_{eff}

- Neutrinos dynamically as important as radiation, but they interact only gravitationally, while radiation is coupled to baryons
- Neutrinos change the matter-radiation equality scale and affect the damping of fluctuations on small scales
- Can parametrize the effective number of neutrinos

$$\rho_\nu c^2 = N_{\mathrm{eff}} \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \rho_\gamma c^2$$

  and fit.
- Planck measures $N_{\mathrm{eff}} = 3.36 \pm 0.34$ - a **nearly** 10σ **detection**
- Neutrinos are not a fancy in a cosmologist's pot smoked brain, but actually seen and measured in real data

$N_{\rm eff}$ and Planck



N_{eff}, *continued*

- The standard model $N_{\mathrm{eff}} = 3.046$ instead of 3, due to
  - neutrino interactions when e^--e^+ annihilation begins
  - the energy dependence of neutrino interactions
  - finite temperature QED corrections
- Since spectral distortions redshift irrespective of energy, their effect is completely encoded into corrections to N_{eff}
- Measurements of N_{eff} to this precision would bring a striking confirmation of our understanding of early universe
- A non-standard N_{eff} means more ultra-relativistic stuff in the early universe - not necessarily neutrinos or fermions, etc.

Can neutrinos be dark matter?

NO!

They free-stream out of over-dense regions, qualitatively changing the structure formation picture from bottom-up to top-down.

BUT! See Alex Kusenko's talk. . .

neutrino mass

- We can assume neutrinos to be ultra-relativistic when they decouple and non-relativistic today
- In that case, their energy density today is given by

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94eV}$$

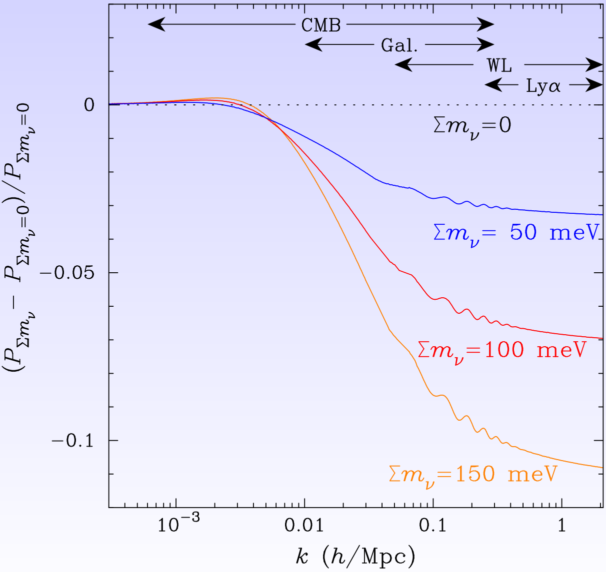
- Ω_ν is the fraction of energy density in neutrinos
- h is the reduced Hubble's constant $h = H_0/(100\mathrm{km/s/Mpc})$
- A mass of 16eV per species would close the Universe, dramatically changing all observations
- Compare this with Tritium-β decay, where limits around $\sim$ 10eV were obtained in 1990s using sophisticated experiments, correcting previous claims of mass detections

effect of the finite neutrino mass

- Neutrinos transition from relativistic to non-relativistic at redshift
$$z \sim 2000 \frac{m_\nu}{1\mathrm{eV}}$$
- Before transition: radiation-like, $\rho \propto a^{-4}$, free stream out of over-dense regions
- After transition: dark-matter like, $\rho \propto a^{-3}$, collapse in over-dense regions
- Small changes in the expansion history of the Universe
- A characteristic suppression on scales smaller than the free streaming wave-number k_f. Averaged over cosmic history, the power is suppressed on scales less than (Lesgourgues & Pastor 06)

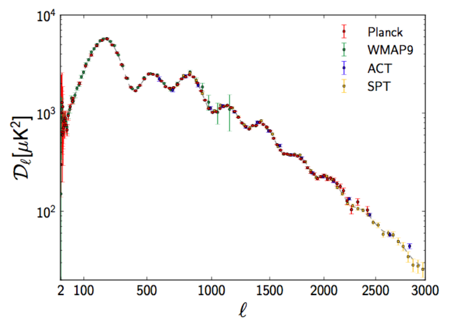
$$k_{\mathrm{nr}} \simeq 0.018 \sqrt{\Omega_m \frac{m_\nu}{1eV}} h/\mathrm{Mpc} \quad (1)$$

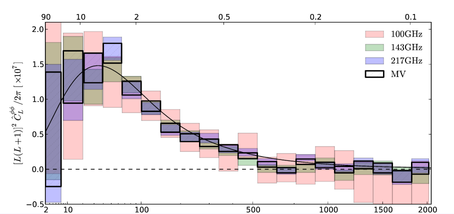
effect of the finite neutrino mass



- Relatively large effects: O(5%)
- Different probes sensitive at different scales
- Measure the unique suppression using one probe
- Combine two probes at two different scales
- **Note characteristic scale and shape of neutrino mass supression.**

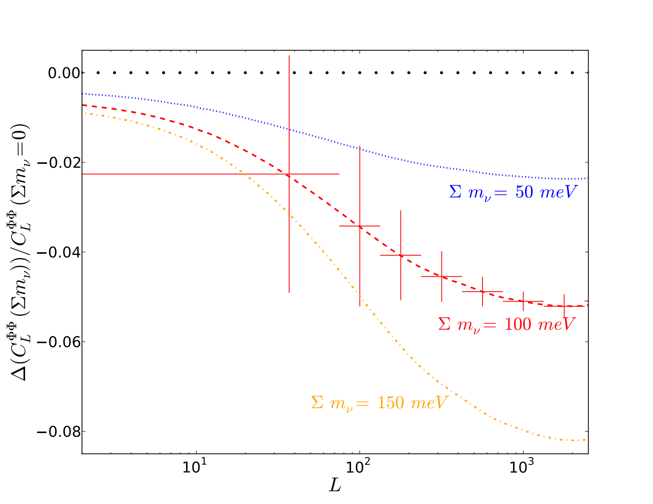
probes: CMB + CMB lensing





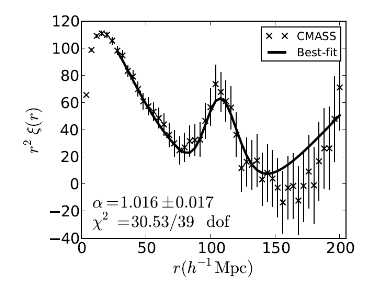
- **See Duncan Hanson's talk**
- Cosmic Microwave Background power spectrum contains enormous amount of information
- Weak lensing of the Gaussian field by intervening structures gives rise to 4-point function that allows one to reconstruct the power spectrum of matter fluctuations along the line of sight
- These fluctuations allow one to measure supression due to neutrino mass
- The highest significance detection of "cosmic shear" to data
- Major systematics: foregrounds, atmospheric fluctuations
- Current limits in conjuction with BAO: $\sum m_\nu < 0.2$ev (at 95% c.l.)

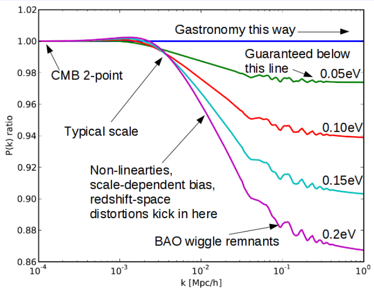
probes: CMB + CMB lensing



Future experiments will reach sensitivity to see neutrino masses (25meV when combined with current BAO data, 16meV with future BAO data)

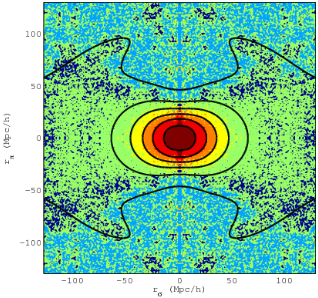
probes: galaxy clustering





Galaxy clustering measures neutrino masses in several ways:

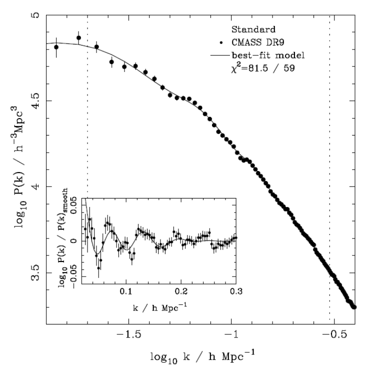
- Through effect on cosmic expansion - positions of BAO wiggles
- Suppression of the power spectrum
- Redshift-space distortions determine bias parameter which allows to measure power at 10 Mpc scales : combine with CMB to get supression



probes: galaxy clustering

Galaxy formation is local:

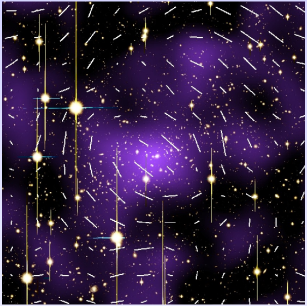
- Decoupling of scales means one gets "effective theory" on large scales
- In the limit of $k \to 0$, biasing, RSD linear
- For $0.1h/\mathrm{Mpc} < k < 0.3h/\mathrm{Mpc}$, biasing, RSD weakly non-linear
- Some confidence we will be able to fit to $k < 0.3h/\mathrm{Mpc}$. For projections we us $k_{\max} \sim 0.2h/\mathrm{Mpc}$
- Major systematics: theoretical modeling, selection function
- Current limits $\sum m_\nu < 0.34\mathrm{eV}/0.15\mathrm{eV}$
- Independently sensitive to 17meV with future data



other probes

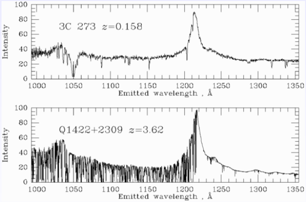
Galaxy weak lensing:

- Galaxy weak-lensing similar in nature as CMB lensing, but with a lower redshift *source* plane
- Despite a similar observable, systematics completely orthogonal
- Major systematics: photo-zs, p.s.f. modeling, shear measurement
- Future sensitivity $\sim$ 25meV



Lyman-α forest:

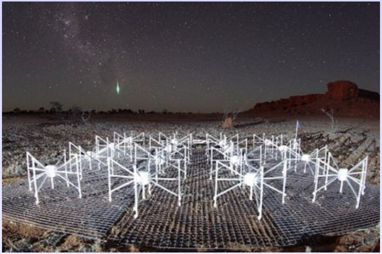
- Measures fluctuations in the spectra of $z > 2.2$ quasars due to Lyman-α absorptions by neutral gas
- Strongest published limit to date: 0.17eV at 95% c.l., updated CMB data would relax this to $\sim$ 0.20eV
- Major systematics: simulations modeling the observed signal, other absorptions



other probes

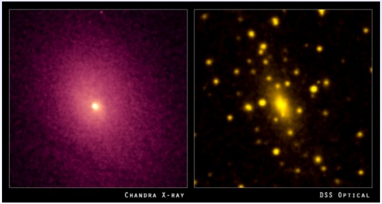
21-cm H spin-flip transition:

- Measures power spectrum of fluctuations in the neutral hydrogen in galaxies (low z) or intergalactic medium (high z)
- Expected signal still to be detected in auto-correlation
- Major systematics: man-made interference, galaxy foregrounds



Clusters of galaxies:

- Measures the number density as a function of mass: exponentially sensitive to amplitude of power spectrum and hence $\sum m_\nu$
- Current limits: ~ 0.3eV
- Major sytematics: mass-observable calibration, modeling of clusters



conclusions

- Cosmology sees neutrinos today
- We will be able to measure neutrino mass in the next decade independently using more than one method
- We should confirm $N_{\rm eff} = 3.046$ with a non-trivial accuracy
- Neutrino masses leave very specific signatures in the data
- Effects are relatively large: 5% at $\sum m_\nu = 100$meV
- Relaxing parameters describing new physics will relax forecasts, but solid statistical analysis can perform model selection and tell us how many parameters do we need
- Let's do it!